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Recent advances in well-based monitoring of CO_2 sequestration

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Abstract

Recent CO_2 sequestration pilot projects have implemented novel approaches to well-based subsurface monitoring aimed at increasing the amount and quality of information available from boreholes. Some of the drivers for the establishment of new well-based technologies and methodologies arise from: (1) the need for data to assess physical and geochemical subsurface processes associated with CO_2 emplacement; (2) the high cost of deep boreholes and need to maximize data yield from each; (3) need for increased temporal resolution to observe plume evolution; (4) a lack of established processes and technologies for integrated permanent sensors in the oil and gas industry; and (5) a lack of regulatory guidance concerning the amount, type, and duration of monitoring required for long-term performance confirmation of a CO_2 storage site. In this paper we will examine some of the latest innovations in well-based monitoring and present examples of integrated monitoring programs.

Keywords: CO2 monitoring; observation well; integrated completion; borehole instrumentation; geological storage

1. Introduction

The primary aim of well-based monitoring within the oil and gas industries is to provide information that can be used to optimize reservoir management and enable safe and economic extraction of oil and gas from the subsurface. Well based-monitoring of oil and gas reservoirs includes a broad array of techniques, using a diverse suite of instruments. During drilling, core is often recovered to permit petrophysical measurements and provide fluid saturation information. Core plugs from the larger core are often extracted to measure permeability and porosity and segments of core can be used to conduct core fluid studies. Wireline logs provide information using non-contact

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methods (e.g. neutrons, seismic and electrical waves) to periodically interrogate the strata. Wireline methods can also be deployed to measure formation pressure and collect samples of formation fluids. In addition, permanently deployed sensors and repeat geophysical surveys can assess temporal changes in the subsurface.

Reservoir management is an important driver for well-based monitoring of CO_2 storage operations. However, additional informational requirements arise during CO_2 emplacement that do not exist during conventional fluid production activities. Owing to potentially complex issues arising from the various national and state regulatory frameworks that will guide CO_2 storage, the plume needs to be constrained to legally available pore space. Furthermore, coupled subsurface processes—including hydrological, mechanical, and geochemical—must be understood to ensure the permanence of the stored CO_2. While CO_2 has been injected in the subsurface for over 30 years in enhanced oil recovery operations, the additional requirement to assure the safe and enduring storage of extremely large volumes of emplaced CO_2 put additional requirements on subsurface monitoring activities.

While tools used for monitoring oil and gas reservoirs have evolved continuously over the last eighty years, large scale implementation of CO_2 sequestration and the deployment of monitoring technologies will need to be extremely rapid if geosequestration is to be an effective tool for mitigating the worst consequences of climate change. Several pilot scale studies have provided an opportunity for testing the performance of traditional well-based methods, along with the development of completely new tools and techniques. This paper highlights some of the results from these early demonstration projects and discusses the potential for integrated borehole monitoring completions to maximize multifunctional data gathering opportunities.

2. Well-based monitoring technologies

Wireline logging

Wireline logging covers a broad array of measurement techniques in which a sonde is trolled through a wellbore and data is transmitted from sensors to the surface for recording. Commonly deployed wireline logs include gamma ray density, formation resistivity, acoustic velocity, self-potential, temperature and pressure. Oilfield service providers have made a continuous effort to increase the quantity and quality of wellbore information with new and more sophisticated tools including formation microimagers (FMI), neutron cross-section capture (Reservoir Saturation Tool), and nuclear magnetic resonance scanners (NMR). In addition to sondes that collect data as they are being trolled through a well, there are wireline tools to collect fluid samples such as the Kuster flow through sampler, Schlumberger's Modular Formation Dynamics Tester (MDT)) and also to retrieve sidewall cores for later analysis.

Several pilot CO_2 storage studies have relied upon standard oilfield tools for characterizing the distribution and saturation of CO_2 in the formation. In the Nagaoka CO_2 injection experiment conducted in a brine saturated sandstone, repeat logging surveys were conducted in three observation wells (Xue et al., 2006). Estimates for CO_2 saturation were developed using decreases in sonic velocity (noted most clearly in p-wave velocities) and increases in resistivity (measured using a dual-induction tool). Based on the data collected at Nagaoka, the travel time from the injection borehole to the observation boreholes was determined along with an estimate for CO_2 sweep efficiency.

The Frio Brine Pilot Test conducted in 2004 consisted of the injection of 1600 Tonnes of CO_2 in a steeply dipping brine saturated sandstone beneath a shale caprock [Hovorka, 2006]. Repeat surveys were conducted using a wire-line deployed reservoir saturation tool (RST), which uses pulsed neutron capture to determine changing brine saturation. Sigma (S), the parameter estimated by the RST tool, is derived from the rate of capture of thermal neutrons (mainly chlorine). The high value of S for formation water derived from brine conductivity allows estimation of S_w and the inverse, CO_2 saturation [Sakurai et al., 2005]. A time-lapse series of five logs in the observation well were collected and are shown in Figure 1. To obtain the images shown, careful corrections needed to be applied to invert the data because of changes in borehole completions. The RST logs display good sensitivity to the presence of CO_2 and with care can be used to infer changes in CO_2 saturation. However, given the open borehole along the perforated zone, it may be difficult to determine the representativeness of the well-based measurements in predicting CO_2 saturation deeper in the formation.

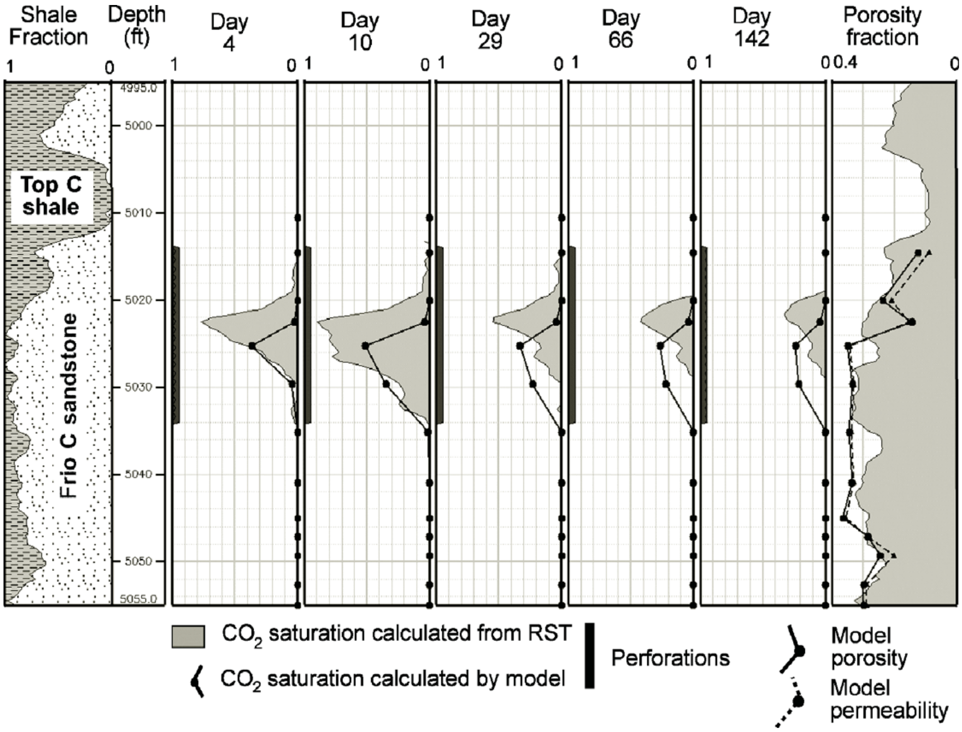

Figure 1. RST logs collected during the Frio Brine Pilot test. CO_2 saturation at the observation well is compared with modeled changes in saturation per layer plotted at layer midpoint.

Geophysical techniques

Early work at Sleipner (Arts et al., 2004) showed the ability of surface seismic to detect and monitor subsurface CO_2. A traditional borehole method to calibrate and augment surface seismic is Vertical Seismic Profiling (VSP), in which seismic sensors are placed in a borehole to record data from surface sources. At the Frio Pilot, time-lapse VSP was successfully demonstrated to detect and map a CO_2 plume in the vicinity of the injection well (Daley, et al, 2007a). While VSP is spatially limited to the vicinity of a well, the near-well region is important to monitor for plume migration. Long term monitoring using the VSP method is more cost effective if permanent sensors are used. Such a permanent deployment was tested at Penn-West (Chalaturnyk, et al, 2006) and a semi-permanent VSP sensor deployment was integrated with other instruments at the Otway Project (Daley et al., 2008). Majer, et al, 2006, are investigating the use of inexpensive shallow 'microholes' for time-lapse VSP monitoring. Borehole sensor deployments also provide excellent microseismic monitoring.

A more unusual type of measurement is crosswell seismic imaging. Crosswell surveys provide tomographic imaging between two wells. Developed for oil reservoir monitoring in the early 1990's, crosswell imaging provides a high resolution (~ 1-10 m) spatial image of subsurface properties. This is important for CO_2 sequestration where understanding the relationship between seismic velocity and CO_2 saturation is essential for quantitative interpretation of surface seismic. At the Frio Pilot, a crosswell survey was successful in imaging the velocity change induced by CO_2 injection (Daley, et al, 2007a, Ajo-Franklin, et al, 2008). Similarly at the Nagaoka Pilot, time-lapse crosswell and sonic logging measured velocity changes induced by CO_2 injection (Saito et al., 2006, Xue et al, 2006).

For the second injection at Frio (Frio-II Pilot) a unique semi-permanent crosswell monitoring scheme was developed (Daley, et al, 2007b) utilizing a tubing-deployed seismic source and sensors. This CASSM (continuous active source seismic monitoring) experiment was able to monitor the development of the CO_2 plume in real time over the course of the 2 week injection with high spatial (~2m) and temporal (~ 15 min.) sampling. Figure 2 shows a schematic of the Frio-II CASSM experiment with a conceptual CO_2 plume after one day (inner short dash) and after two days (outer long dash), with measured delay times at three sensor depths over three and a half days of CO_2 injection (right).

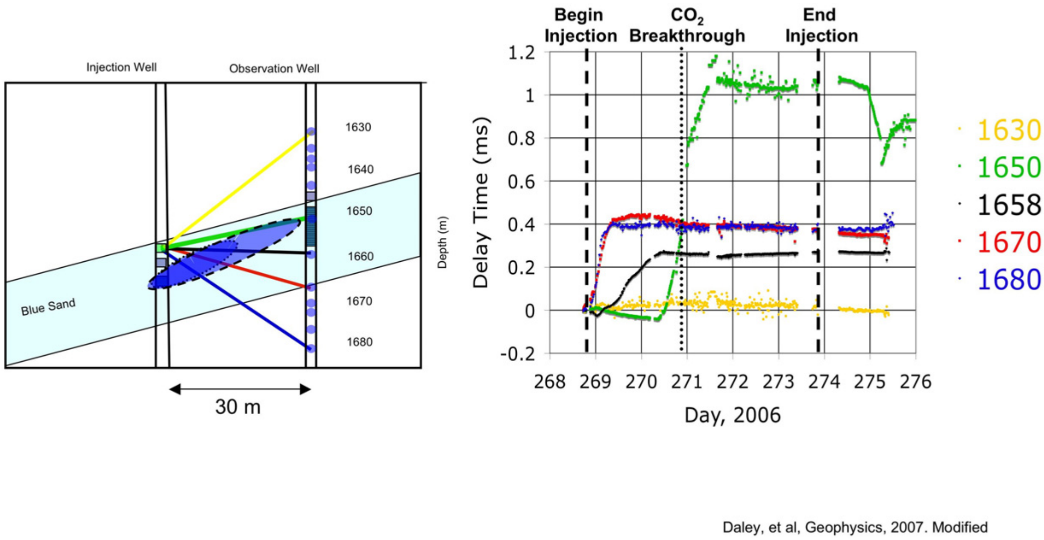

Figure 2. Schematic of Frio-II seismic monitoring experiment with conceptual CO2 plume after one day (inner short dash) and after two days (outer long dash), with measured delay times at three sensor depths over three and a half days of CO2 injection (right).

Geochemical Sampling

Geochemical sampling is used to assess CO_2-rock-water interaction in order to better understand the ultimate fate of emplaced CO_2 and assess the integrity of reservoir seals. There are numerous techniques for acquiring downhole fluid samples. Where reservoir operations support continuous productions of fluids, such as at CO_2 EOR sites (e.g. Weyburn Field), wellhead samples provide fluids for geochemical analysis. At many CO_2 injection sites, observation wells may play a passive monitoring role, where periodic production of large volumes of fluids may be operationally difficult and lead to degassing and disturbance of sample integrity. Numerous methods have been devised to obtain representative downhole samples while maintaining reservoir pressure conditions.

At the Frio Brine Pilot experiment, pre-CO_2 injection samples were collected by deploying both Kuster flow-through samplers and Schlumberger's MDT tool [Kharaka et al., 2006]. However, it was determined that during the active CO_2 injection period, the repeated running of a wireline was not operationally feasible and would interfere with other planned measurements. Based on the spatial limitations that arose from the co-deployment with a string of hydrophones and a pressure/temperature gauge, a new small diameter permanently deployable geochemical sampler, referred to as a U-tube sampler [Freifeld et al. 2005] was developed. The U-tube sampling system (Figure 3) utilizes compressed gas to force the fluid to be sampled through a small diameter tube that goes down to the zone of interest and returns to the surface, forming a ''U.'' A short stinger with a check valve runs through a pneumatic

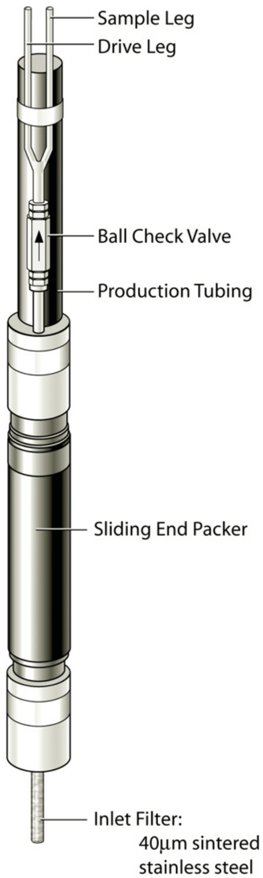

Figure 3. Details of the U-Tube sampling system downhole assembly. When the drive and sample legs are depressurized by venting purge gas, downhole fluid enters the U-tube through the inlet filter. By hydrostatic pressure, fluid is forced through the check valve until the head in the tubing equals the hydrostatic head in the reservoir, at which time the check valve closes. The sample is recovered by pressurizing the drive leg and collecting the fluid from the sample leg.

packer, used to isolate the perforated section of the well bore, and terminates at an inlet filter sitting in formation fluid. To minimize alteration of the sampled fluids, the fluid that is forced up the U-tube sample line is collected in pre-evacuated cylinders and driven into the cylinder until the cylinder matches formation pressure. To determine the density of the sampled, which is required to determine the ratio of supercritical CO_2 to brine, strain gages were mounted beneath each cylinder. Field measurements of ephemeral properties such as alkalinity and pH were performed along with real-time analysis of fluid gas composition using a portable quadrupole mass spectrometer [Freifeld and Trautz, 2006]. Additional samples in both pressurized and non-pressurized containers were collected for subsequent laboratory analysis.

Integrated well-based monitoring

Because of the high cost of drilling and completing deep wellbores, there are strong pressures to maximize the data collected. Traditionally, measurements would be performed sequentially within a borehole, with the installation and removal of purpose built equipment for each independent measurement. The oil and gas industries have slowly moved to the incorporation of permanent downhole sensors, such as to permit continuous pressure and temperature monitoring while providing access for acquiring wireline logs. Recent CO_2 storage pilot studies, with a need to more fully understand the movement and distribution of CO_2, have incorporated significantly more sophisticated strings of multi-function permanently deployed sensors, while still facilitating access for wire-line deployed instruments, in what is referred to as integrated well-based monitoring. The term “integrated” arises from the simultaneous deployment of multiple sensor strings and data survey methods without a need for costly well-workover operations.

Examples of integrated well-based monitoring systems can be found at (1) the Frio-II experiment, Dayton, Texas, USA [Daley et al, 2008], (2) the Penn West Pilot, Alberta, Canada [Chalaturnyk et al., 2006], (3) CO_2SINK, Ketzin, Germany [Giese et al., 2008], and (4) the Otway Project, Victoria, Australia [Freifeld et. al., 2008a]. For the Frio-II pilot test, a string of 24 hydrophones was deployed concurrently with a U-tube geochemical sampler and a pressure/temperature transducer, strapped onto a 2-3/8” conductor pipe in an observation borehole. As previously discussed, a tubing deployed piezo-electric seismic source facilitated continuous imaging of the CO_2 plumes movement between the injection and observation boreholes. Simultaneous U-tube fluid sampling was carried out along with periodic RST wireline surveys. At the Frio-II Pilot, reductions in seismic travel time up to 8% were observed as the CO_2 plume crossed the raypaths between the source and receivers. At the Penn West Pilot, two fluid samplers, a string of eight geophones, and six pressure/temperature sensors were tubing deployed to monitor a nearby CO_2 injection [Chalaturnyk et al., 2006]. A unique diagnostic data set was collected during cementing operations, where pressure transients were revealed some difficulties in annular isolation because of conduits along the cemented zones.

The Otway Project is the first demonstration project for storage of CO_2 (~100,000 Tonnes) in a depleted gas field. To understand the changes in the reservoir induced by the CO_2 injection, an existing decommissioned slim gas production well (3.5” casing) located near the crest of an anticline was recompleted as a monitoring borehole. Three U-tube samplers were installed, with one in the remnant post production gas cap, and two beneath the current gas water contact in the residual gas zone, to observe the hydrologic and geochemical changes occurring as the reservoir fills with supercritical CO_2 and the gas-water contact is pushed down. A string of 24 sensors (21 geophones and 3 hydrophones) permitted three distinct seismic measurements: (1) high resolution travel time through the reservoir; (2) walkaway vertical seismic profiling; and (3) passive microseismic monitoring. In addition, two pressure/temperature gages were installed but failed to function properly. Data collection at the Otway site is ongoing, with weekly geochemical sampling and bimonthly seismic surveys.

Within the framework CO_2SINK project about 60,000 Tonnes of CO_2 are planned to be injected into a saline formation at Ketzin, Germany [Schilling et al, 2008]. In 2007, one injection borehole and two nearby monitoring wells have been drilled and completed with integrated monitoring systems [Prevedel et al., 2008]. Cemented along the outside of the casing of each well are electrodes for conducting electrical resistivity tomography surveys, along with fiber-optic distributed temperature sensors (DTS) [Giese et al., 2008]. The inside of each wellbore is available for periodic wireline logging, crosswell seismic surveys and gas sampling.

One instrument being used at CO_2SINK, not previously deployed during a CO_2 sequestration experiment, is the recently developed distributed thermal perturbation sensor (DTPS) [Freifeld 2008b]. The DTPS provides estimates for CO_2 saturation in the formation by proxy measurement of formation thermal conductivity. Since formation thermal conductivity is a function of rock matrix conductivity and fluid conductivity, any increase in CO_2 saturation and corresponding decrease in brine saturation will result in a reduction in bulk thermal conductivity. To perform a DTPS measurement an electrical heater (consisting of a loop of wire) was installed along with the DTS fiber-optic cables. The heater is energized for 48 hours, providing approximately 20 W/m of heat along the wellbore. Given the 1 m spatial resolution of the DTS, the thermal transients recorded can be inverted to provide estimates for thermal conductivity, and hence also CO_2 saturation with correspondingly high spatial resolution. Figure 4 shows baseline data collected with the DTPS for the Ktzi 201 and Ktzi 202 wells. Preliminary results of numerical inversions of the measured heating curves for thermal conductivity show a good correlation to measurements on core samples. As CO_2 injection progresses at CO_2SINK, the CO_2 saturation in the formation around the injection and observation boreholes is expected to increase, resulting in a measureable reduction in the formation's thermal conductivity.

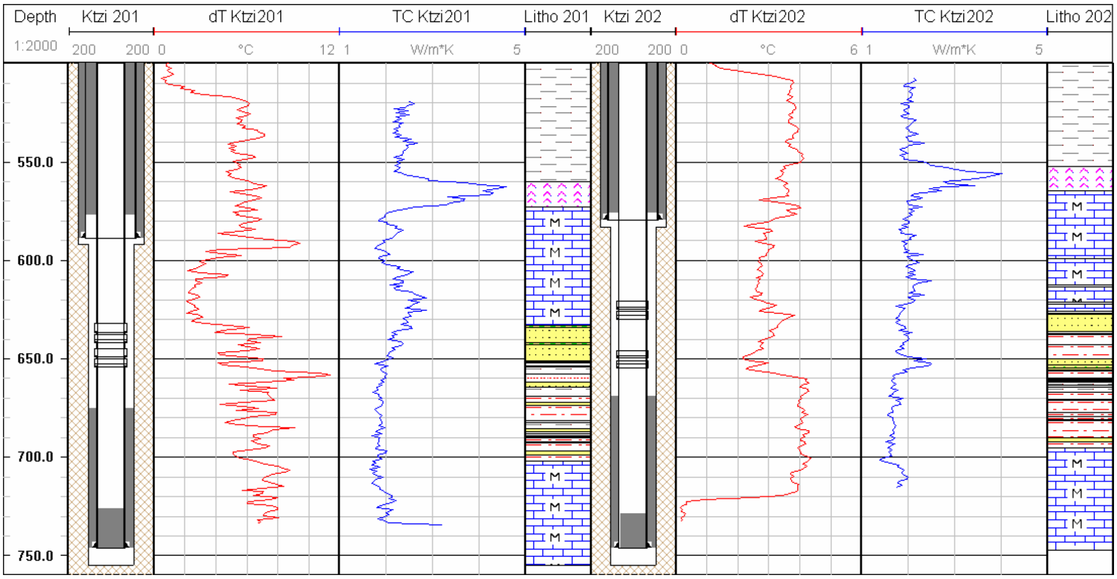

Figure 4. Well logs for Ktzi201 and Ktzi202 showing temperature changes (dT) during DTPS heating and calculated thermal conductivities (TC) along with well layouts and lithologies.[after Förster et al., 2008]. Note that at a depth of ~560 m there is an anhydrite rich marker bed which is indicated by elevated thermal conductivities.

3. Conclusions

Many standard oilfield tools such as sonic and dual induction logs are readily adaptable for monitoring CO_2 storage in reservoirs. Seismic surveys are particularly sensitive to changes in the seismic properties as CO_2 replaces water in the formation. While existing tools will most likely serve as the basis for future monitoring programs owing to their history and familiarity, newly developed instruments that are sensitive to property changes caused by emplaced CO_2 are also being exploited. The DTPS monitors reductions in thermal conductivity that arise from the low thermal conductivity of CO_2 compared to brine. The U-tube sampler has been demonstrated at both the Frio Brine Pilot and the Otway Project as being capable of collecting relatively uncontaminated samples of multi-phase fluids at reservoir pressure. Additional laboratory studies will be required to understand the effects of variable CO_2 saturation on seismic and electrical properties; as these studies are conducted, well-based geophysical surveys will be able to estimate CO_2 saturation. The numerous world-wide CO_2 storage demonstration projects and progress towards commercial-scale sequestration is resulting in the rapid adoption of existing and new tools and technologies for monitoring CO_2 storage in the subsurface.

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